

PATENT

INSTITUT FRANÇAIS DU PETROLE

**METHOD FOR DETERMINING THE RESISTIVITY INDEX, AS A FUNCTION  
OF THE WATER SATURATION, OF CERTAIN ROCKS  
OF COMPLEX POROSITY**

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ABSTRACT

- Method for determining the variations of the resistivity index (RI) of a family of rock samples of complex pore structure with at least two pore networks, as a function of the water saturation ( $S_w$ ), and in the presence of a non-oil conducting fluid.
- The volume fraction ( $f_1, f_2, f_3$ ) occupied by each pore network and the distribution of the pore throats in the various pore networks are determined for each sample of the family. The values of coefficients relating the variation of its electrical resistivity as a function of its water saturation ( $S_w$ ) are experimentally determined on a sample of the family used as a reference sample. The resistivity index (RI) of all the samples of the family is then determined on the basis of the variation of parameters describing the layout of the pore network, and using the values of said coefficients measured on the reference sample. The method allows to measure a continuous resistivity index curve which is not obtained, as in conventional techniques, from only a limited number of points at capillary equilibrium.
- Applications : petrology for example.

## FIELD OF THE INVENTION

The present invention relates to a method for determining the resistivity index RI, as a function of the water saturation, of certain rocks of complex porosity.

The method according to the invention finds applications notably in the sphere of  
5 hydrocarbon reservoir development.

Evaluation of carbonate reservoirs is a particularly difficult task for petrophysicists, who still lack precise knowledge concerning the carrying properties within these porous media. In relation to siliclastic rocks, carbonates may be simpler on the mineralogical plane, but they are incomparably more complex in terms of pore structure and surface  
10 properties. The largely biological origin of the sediments, combined with various diagenetic processes, leads to complex pore structures that may be very different from one reservoir to the next. For many carbonate systems, resistivity data calibrations carried out in the laboratory contradict the observations made in the field (anhydrous production, capillary pressure) and the direct water saturation measurements performed  
15 on preserved cores.

## BACKGROUND OF THE INVENTION

The prior art is notably defined by the following publications :

- Bouvier L. et al., Reconciliation of Log and Laboratory Derived Irreducible Water Saturation in a Double Porosity Reservoir, Advances in Core Evaluation, edited by  
20 Worthington and Longeron, Gordon and Breach Science Publishers,

- Dixon J.R. et al. (1990), The Effect of Bimodal Pore Size Distribution on Electrical Properties of some Middle Eastern Limestone, Soc. Petr. Eng. 20601, 7<sup>th</sup> SPE Middle Eastern Oil Show, Bahrain, pp.743-750,
- Fleury M. (1998), « FRIM : a Fast Resistivity Index Measurement Method », Proceedings of the International Symposium of the Society of the Core Analysts, Den Hague,
- Fleury M. et al. (2000) « Frequency Effect on Resistivity Index Curves Using a New Method », Proceedings of the 41<sup>st</sup> Annual SPWLA Symposium, Dallas,
- Moore C.H. (2001) « Carbonate Reservoirs, Porosity Evaluation and Diagenesis in a Sequence Stratigraphic Framework », Developments in Sedimentology 55, Elsevier Editions,
- Petricola M.J.C. et al. (1995) « Effect of Microporosity in Carbonates : Introduction of a Versatile Saturation Equation », Soc. Petr. Eng. 29841, SPE Middle Eastern Oil Show, Bahrain, pp.607-615,
- Sen P.N. et al. (1997) « Resistivity of Partially Saturated Rocks with Microporosity », Geophysics, Vol.62, No.2, pp.415-425.

Understanding and prediction of the effect of the structure of the pore network, of the wettability and of the electrical properties of carbonate rocks is a real scientific challenge, theoretically as well as experimentally. In fact, correct evaluation of these parameters has a major impact on estimation of the oil in place, notably for Middle Eastern giant fields, because the difference in relation to the standard values of Archie's exponents  $m$  and  $n$  in relation to value 2 is so great that estimation of the water saturation can vary by more than 20 %.

Various experimental observations have shown the existence of distinct pore populations : micropores, macropores and mesopores, with different coexistence degrees. In general, the resistivity index curve  $RI(S_w) = R_t(S_w)/R_o$ , where  $R_t$  is the resistivity of the rock to a water saturation  $S_w$ , and  $R_o$  the resistivity for  $S_w=1$ , cannot  
 5 be described by a power law (second Archie's law  $RI = S_w^{-n}$ ), i.e.  $n$  is a function of the saturation itself. Microporosity can act as a parallel path for the current, which leads to a decrease in the values of  $n$  and, therefore, to a gradual insensitivity of the resistivity to saturation, as observed on clayey sands. Microporosity can also be the cause of the low measured values of  $n$  (typically 1.45). It has also been observed that  $n$  can increase  
 10 considerably under certain conditions, and there might be a connection between curve  $RI(S_w)$  and the capillary pressure curve. The increase in the values of  $n$  is also a known effect of the wettability, which tends to favour aqueous phase discontinuity and therefore to increase the resistivity to water wettability. The effect of the wettability can lead to either a sudden increase of  $n$ , or to a high value  $n$  without discontinuity, which  
 15 can lead to confusion.

The experimental curves  $RI(S_w)$  which have been drawn from various prior works, already mentioned above, and from our own observations can have (Fig.1) four distinct shapes which do not always meet Archie's laws :

- type I : can be typical of carbonates from the Thamama formation,
- 20 - type II : straightens at intermediate saturation and flattens at low saturation (present study),
- type III : single slope at low saturation, extrapolation at  $S_w=1$  above  $I_r=1$ , and

- type IV : typical of oil-wet systems, high values of  $n$  that can increase further at low saturation. This is also valid for clasts.

It can thus be seen that, in the presence of rocks of complex porosity which do not meet Archie's laws, a large number of costly measurements is necessary to take account  
5 of the variability of the pore structure.

### SUMMARY OF THE INVENTION

The object of the method according to the invention is to determine the variations of the resistivity index (RI) of a family of rock samples of complex pore structure as a function of the water saturation ( $S_w$ ), in the presence of a non-conducting fluid. It  
10 comprises the following stages :

- for each sample of the family comprising at least a first and a second pore network, determining the volume fraction occupied by each pore network by applying to the various samples an NMR type relaxometry technique,
- for each sample of the family, measuring by mercury injection the pore throat  
15 distribution in the various pore networks,
- determining experimentally on a sample at least of the family used as reference the values of coefficients relating the variation of its electrical resistivity as a function of its water saturation, and
- determining the resistivity index (RI) of all the samples of the family on the basis of  
20 the variation of parameters describing the layout of the pore network and using the values of the coefficients measured on the reference sample.

According to a first implementation mode suited for samples comprising two pore networks, the values of the coefficients relating the total conductivity of the sample to the conductivity of the first and second pore networks and to the respective water saturations of the two networks are determined from the reference sample, the resistivity index being calculated from the respective volume fractions of the two pore networks and from the value of the mean saturation from which the network with the smaller pores is invaded by the non-conducting fluid.

According to a second implementation mode suited for samples comprising a third pore network, the values of the coefficients relating the total conductivity of the sample to the conductivity of the first and second pore networks and to the respective water saturations of the first two networks are determined from the reference sample, the resistivity index being calculated from the respective volume fractions of the three pore networks, from the value of the mean saturation from which the network having the smaller pores among the first two pore networks is invaded by the non-conducting fluid, and from the value of the mean saturation from which the network having the larger pores among the first two pore networks is invaded by the non-conducting fluid.

The resistivity index variations obtained by applying the method are in best agreement with the experimental curves whose examples are illustrated in Fig.1. The method is based on a powerful experimental technique allowing to measure a continuous resistivity index curve, unlike the conventional technique which describes curve RI only by a limited number of points at capillary equilibrium.

## BRIEF DESCRIPTION OF THE FIGURES

Other features and advantages of the method and of the device according to the invention will be clear from reading the description hereafter, with reference to the accompanying drawings wherein :

- 5 - Figure 1 shows a diagrammatic representation, in logarithmic coordinates, of various types of curves RI as a function of the water saturation  $S_w$  observed experimentally ; curves I to III are due to the pore structure, curve IV is typical of the effects of the wettability and it is not specific to carbonates,
- Figure 2 shows a pore size distribution of three carbonates studied : (reservoir  
10 carbonate, Estailade limestone and Brauvillier limestone) obtained by NMR ; the figures indicate the pore volume fraction to the left of the vertical segment,
- Figures 3a, 3b show the sensitivity of the model with two pore networks (DPC) to the saturation  $S_c$  at which the micropores are invaded by oil (3a) and to  $\alpha$ , initial conductivity ratio of the two pore populations (3b),
- 15 - Figures 4a, 4b show the application of model DPC to sample RC at ambient temperature (4a) and under the reservoir conditions with dead oil (4b) ; the experimental curve is drawn in thin line and the model in thick line ; parameters  $n_1$ ,  $n_2$  and  $\alpha$  are adjusted,  $f_1$  and  $S_c$  are measured,
- Figure 5 shows an invasion scenario in the model with three pore networks (TPC),
- 20 - Figure 6 shows an electrical layout modelling the three networks in the TPC model,
- Figure 7 shows a measured (thin line) and model (thick line) curve RI for sample EL (Estailade limestone),

- Figure 8 shows a measured (thin line) and model (thick line) curve RI for sample BL (Brauillier limestone), and
  - Figure 9 shows a simplified calibration sequence for the resistivity logs ; for non-Archie type rocks,  $Sw(RI)$  is necessary ; the laboratory data generally provide relation
- 5 RI( $Sw$ ).

### DETAILED DESCRIPTION

We have a certain number of samples of the same family and we want to calculate the resistivity index of each one. The method described hereafter allows these indices to be obtained, notably from :

- 10 - experimental measurements performed on each sample of the family, giving the number of pore networks of different size and the volume fraction occupied by each pore network, as well as the pore throat distribution for each one, and
  - an experimental measurement performed on a single sample of the family, used as a reference sample, of the variation of its electrical resistivity as a function of its water
- 15 saturation ( $Sw$ ).

### Nomenclature

- Cto = total conductivity at  $Sw=1$
- $C_i$  = conductivity of the i-th population at  $Sw_i=1$
- $f_i$  = NMR volume fraction of pores of the i-th population,  $i=1,2,3$
- 20 RI = resistivity index,  $R_t/R_oSw$  = mean water saturation
- $Sw_i$  = water saturation of the i-th pore population
- Sc = mean saturation at which the micropores are invaded



$S_m$  = mean saturation at which the macropores are invaded

$\alpha_{1,2}$  = conductivity ratio  $C_1/C_2$  and  $C_1/C_3$  respectively.

### Experimental data on samples

#### *NMR relaxation time measurements*

5        The various pore networks within the rock samples and the volume fraction occupied by each network are first determined by means of an NMR type relaxometry method well-known to specialists. An example of such an NMR relaxometry method is for example described in French patent application EN-02/... filed by the applicant.

10        We present the measurements performed on three selected carbonate samples. By applying an NMR type relaxometry method known to specialists, we can see that all the samples are characterized by a double or triple pore size distribution. The first one is a reservoir carbonate sample from the Middle-East, classified as a packstone. It was cleaned by means of different solvents at high temperature before being subjected to the measurements. Under ambient conditions, the experiment was carried out with refined  
15        oil and synthetic reservoir brine. The experiment carried out under reservoir conditions was conducted with filtered degassed reservoir oil at the reservoir pressure. After cleaning, the wettability of the sample is characterized by a moderate water wettability and, after aging, by a high oil wettability. The other two samples are outcrop carbonates (water-wet). The porosity of the Brauvillier limestone (BL) is essentially intergranular  
20        and due to the oolite cortex. The porosity of the Estailade limestone is both inter and intragranular. The pore populations are separated by a factor 10 at least.

### *Resistivity index measurements*

The resistivity index of the samples is then measured. The fast resistivity index measurement method (FRIM) described in patent EP-974,839 filed by the applicant can be advantageously used.

5        According to this method, a forced oil-water displacement is carried out on a small core of length 2.5 cm and diameter 4 cm for example. This displacement is very close to a porous plate displacement method, except that capillary equilibrium is not necessary. Under ambient conditions, only two or three pressure stages are used. Under reservoir conditions, when dead or crude oil is used, each pressure stage is prolonged for the time  
10       required to obtain wettability stabilization at a given saturation. Drainage is thus carried out in approximately two to three weeks, which typically corresponds to the kinetics of the chemical processes linked with aging. The simplicity of this method lies in the fact that it just requires real-time recording and plotting of the mean saturation and resistance to obtain a continuous resistivity index curve free of any artefact. The key  
15       point is due to the fact that the radial geometry of the electrodes allows to examine the whole volume of the sample and to compensate the non-uniform saturation profile which appears in the absence of capillary equilibrium.

Under ambient conditions, we used the radial-electrode cell described for example in the aforementioned patent EP-A-974,839. The complex impedance measurements  
20       were carried out at a fixed frequency of 1 kHz and the real part was extracted to calculate the resistivity index. The highest capillary pressure applied was 12 bars (for an interfacial tension  $\gamma=35$  mN/m ; under reservoir conditions, with crude oil, the maximum capillary pressure was reduced proportionally to the interfacial tension).

## Conductivity models

### *Double-porosity conductivity model (DPC)*

The goal is to explain the bending of curves RI at low saturation (type I, Figure 1). The double-porosity model considered here is basically very close to those proposed for clayey sands, where the clays present at the surface of the pores constitute a parallel path for the current. For carbonates, we assume the existence of two pore networks having parallel electrical conductivities. The two main ingredients in our model are the description of the pore network invasion during drainage and the description of the electrical layout of the two different pore populations.

The first network 1 (macropores for example) represents the major part of the pore volume, whereas the second network 2 (micropores) only represents a small fraction thereof, which is not necessarily greater than the percolation thresholds. We first consider the saturation of each network,  $Sw_1$  and  $Sw_2$ , which are related to the measured mean saturation  $Sw$  by :

$$Sw = f_1 Sw_1 + f_2 Sw_2 \quad \text{where} \quad f_1 + f_2 = 1 \quad (1).$$

$f_1$  and  $f_2$  represent the pore volume fraction of each population. These fractions were evaluated by means of the NMR relaxometry technique. We then assume that the networks are invaded by oil at different capillary pressures ; the oil reaches the small pores at a higher pressure than the pressure observed for the larger pores. From the capillary pressure curve previously drawn, this pressure corresponds to a mean saturation  $Sc$  which can be deduced from the curves obtained by mercury injection (showing the pore throat distribution).  $Sw_1$  can be expressed as a function of  $Sw$  at high saturation  $Sw$  :

$$S_{w_1} = \frac{S_w + f_1 - 1}{f_1}, S_{w_2} = 1 \text{ for } S_w \geq S_c \quad (2)$$

Below  $S_c$ , relations  $S_{w_1}=f(S_w)$  and  $S_{w_2}=f(S_w)$  require other hypotheses. We assume (i) a linear relation and (ii) that  $S_{w_1} \rightarrow 0$ ,  $S_{w_2} \rightarrow 0$  when  $S_w \rightarrow 0$ .

We deduce that :

$$\begin{aligned} S_{w_1} &= \frac{f_1 + S_c - 1}{f_1 S_c} S_w, \\ S_{w_2} &= \frac{S_w}{S_c} \text{ for } S_w \leq S_c \end{aligned} \quad (3)$$

5

We now consider the conductivity of each network. In case of an initial brine saturation, the total conductivity  $C_{t_0}$  for the two networks in parallel will be :

$$C_{t_0} = C_1 + C_2 = C_1 (1 + \alpha) \text{ where } C_2 = \alpha C_1 \quad (4).$$

Parameter  $\alpha$  is the conductivity ratio of the two 100 % saturated networks. From  
 10 Archie's first law, we assume that  $C_1$  and  $C_2$  are related to the pore volume fraction of each population and, therefore, that  $\alpha$  is of the order of ratio  $f_2/f_1$ . When the two networks are invaded by oil, we assume that each conductivity is related to the saturation by a power law (as in Archie's second law). The total conductivity in the two saturation ranges is as follows :

$$15 \quad C_t = S_{w_1}^{n_1} C_1 + C_2 \text{ for } S_w \geq S_c \quad (5)$$

$$C_t = S_{w_1}^{n_1} C_1 + S_{w_2}^{n_2} C_2 \text{ for } S_w \leq S_c \quad (6).$$

By means of equations 4, 5 and 6, we find resistivity index RI as follows :

$$RI = \frac{Ct_o}{Ct} = Sw_1^{-n_1} \frac{1 + \alpha}{1 + \alpha Sw_1^{-n_1}} \text{ for } Sw \geq Sc \quad (7)$$

$$RI = Sw_1^{-n_1} \frac{1 + \alpha}{1 + \alpha Sw_1^{-n_1} / Sw_2^{-n_2}} \text{ for } Sw \leq Sc \quad (8)$$

When a pore population is in the dominant position (network 1 in the present case), functions RI are governed by the resistivity properties ( $n_1$ ) of this population. Equations 7 and 8 are essentially similar to the formulas used for clayey sands, except that we introduce a second exponent  $n_2$  which characterizes the second network.

In the DPC model, there are in total 4 parameters  $n_1$ ,  $n_2$ ,  $\alpha$  and  $Sc$ . For a given experimental curve,  $Sc$  is measured separately during a mercury injection experiment, whereas the other parameters are adjusted. A variation range is however observed for  $\alpha$  around  $f_2/f_1$ , for which a physical explanation exists. At high saturation  $Sw$ , the slope on the log-log scale of  $RI(Sw)$  is  $-n_1$  and, at low saturation, the slope is  $-n_2$ . To a certain extent,  $Sc$  and  $\alpha$  compensate for one another (Figure 3), but  $\alpha$  is the most sensitive parameter which controls the final value of RI. One can note that the case  $Sc=0.05$  presented in Figure 3 corresponds to a situation where the second network is not invaded by oil, which gives a horizontal asymptote.

The parameters of the model were adjusted in order to correspond to the experimental curve RI measured on sample RC. The value of  $Sc=0.4$  was deduced from the elbow of the capillary pressure curve obtained by mercury injection and the volume fraction  $f_1=0.88$  macropores (network 1) was deduced by NMR (Figure 2). Despite the low permeability of the sample, the lowest saturation obtained is very low (4 %), which allows good determination of the parameters of the model under ambient conditions.

The initial slope of curve RI is  $n_1=1.71$  ; it characterizes network 1. Network 2 is very weakly sensitive to saturation ( $n_2=0.25$ ) and does not behave like a standard network. However, the initial conductivity ratio  $\alpha=0.054$  of network 1 to 2 is of the order of  $f_2/f_1=0.136$ . Under reservoir conditions (oil wettability conditions), a high increase of  $n_1$  is observed, but curve RI is still not linear on the log-log scale. Characteristics  $n_2=0.78$  and  $\alpha=0.11$  of the second network are also slightly modified, but the precision concerning these parameters is lower than under ambient conditions because the saturation reached (at the same capillary pressure) is much higher and close to  $Sc$ .

*Approximate formula in the case of the DPC model*

We propose an approximate formula reducing relations 7 and 8 to a single formula, which is valid for the type I curves. We first note that :

$$Sw_2^{n_2} Sw_1^{-n_1} \approx Sc^{-n_2} Sw^{n_2-n_1} \approx Sw^{n_2-n_1}$$

$$\text{with } Sw_1 \equiv Sw \text{ and } Sc^{-n_2} \approx 1 \quad (15)$$

which gives  $f_2 \ll f_1$ . Since  $n_2 \ll n_1$ , equations 7 and 8 can be approximated by :

$$RI = Sw^{-n_1} \frac{1+C}{1+CSw^{n_2-n_1}} \quad (16).$$

As can be seen in Figure 10, using the 3 parameters  $n_1$ ,  $n_2$  and  $C$  is sufficient to describe the data with precision by means of equation 16. Here, the meaning of  $C$  is approximately the same as  $\alpha$  and it can depend on the temperature. The formulation given in equation 16 can be used to describe standard experiments carried out at capillary equilibrium where only a limited number of points is available.

*Triple-porosity conductivity model (TPC)*

The goal is to explain the straightening of curves RI at intermediate or high saturation, and their bending at low saturation on the log-log scale (types II and III, Figure 1). We use here the general idea according to which complex carbonates can have three pore populations referred to, for simplification reasons, as micro, macro and mesopores (3, 2 and 1 respectively). As in the double-porosity model, we consider the saturation of the 3 populations :

$$Sw = f_1 Sw_1 + f_2 Sw_2 + f_3 Sw_3 \quad \text{where} \quad f_1 + f_2 + f_3 = 1 \quad (9)$$

Here again, we assume that the invasion of these populations by oil during drainage is sequential. If network 1 is invaded first, we define a mean saturation  $Sm$  at which network 2 is invaded :

$$Sw_1 = \frac{Sw - f_2 - f_3}{f_1},$$

$$Sw_2 = 1 \quad Sw_3 = 1 \quad \text{for} \quad Sw \geq Sm \quad (10)$$

Below  $Sm$ , it is possible to imagine many scenarios. In general, we assume linear relations for functions  $Sw_1(Sw)$  and  $Sw_2(Sw)$ . According to a possible scenario, we assume that  $Sw_1 \rightarrow 0$ ,  $Sw_2 \rightarrow 0$  when  $Sw \rightarrow Sc$ .  $Sc$  is the saturation at which the micropores are invaded. It follows therefrom that :

$$Sw_1 = \frac{Sw - f_2 Sw_2 - f_3}{f_1}, \quad Sw_2 = \frac{Sw - Sc}{Sm - Sc},$$

$$Sw_3 = 1 \quad \text{for} \quad Sc \leq Sw \leq Sm \quad (11)$$

This invasion scenario is summarized in Figure 5. Typically, one thinks of a situation where  $f_3 \ll f_1$  and  $f_1 \approx f_2$ , and the micropores (network 3) are invaded at a pressure that is much too high to be observed during the experiment.

Consider now the conductivity of these populations. We assume that networks 1 and 2 are in series, whereas network 3 is in parallel as shown in Figure 6. The arrangement in series may seem to contradict a sequential invasion by oil (which is an essentially parallel mechanism), but such a situation is possible. At  $Sw=1$ , conductivity  $C_{t0}$  of the system shown in Figure 6 is as follows :

$$C_{t0} = (C_1^{-1} + C_2^{-1})^{-1} + C_3 = C_1 [(1 + \alpha_1^{-1})^{-1} + \alpha_2]$$

$$10 \quad \text{where } C_2 = \alpha_1 C_1, C_3 = \alpha_2 C_1 \quad (12).$$

In the two saturations ranges, we obtain :

$$C_t = C_1 [(Sw_1^{-n_1} + \alpha_1^{-1})^{-1} + \alpha_2] \text{ for } Sw \geq S_m \quad (13)$$

$$C_t = C_1 [Sw_1^{-n_1} + Sw_2^{-n_2} \alpha_1^{-1})^{-1} + \alpha_2] \text{ for } S_c \leq Sw \leq S_m \quad (14).$$

The resistivity index can be calculated from equations 12 to 14. For the measured values of  $f_1$ ,  $f_2$  and  $f_3$ ,  $n_1$ ,  $n_2$ ,  $\alpha_1$  and  $\alpha_2$  have to be adjusted to the experimental data. As in the DPC model,  $\alpha_1$  is expected to be of the order of  $f_2/f_1$  and  $\alpha_2$  of the order of  $f_3/f_1$ .

This model was tested with resistivity index curves measured on samples EL and BL. On sample EL (Figure 7), straightening of the curve at high saturation is reproduced qualitatively at high saturation and flattening at low saturation is reproduced. We observe a discontinuity at  $S_m$  (deduced from the elbow of the capillary pressure curve obtained by mercury injection) because of a sudden modification of relation  $Sw_1(Sw)$  (as shown in Figure 5). After adjustment, the two dominant pore